Observations of the CALIFORNIA INSTITUTE OF TECHNOLOGY RADIO OBSERVATORY

Owens Valley, California

1960

5. THE DISCRETE SOURCES OF COSMIC RADIO EMISSION

by

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The Discrete Sources of Cosmic Radio Emission*

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One of the principal problems in the radio astronomy of the discrete sources is their identification with visible objects. Identification is necessary in most instances to determine the distance of a source and thus its intrinsic luminosity. It is of assistance in deciding the probable mechanism for the radio emission. Identification of a reasonable sample of radio sources should be made prior to speculations from statistical studies of the radio sources as a class.

A proper identification can be obtained in a number of ways, depending on the particular circumstances. In the case of a planet, detection of the motion is sufficient confirmation of radio emission. Both the radio spectrum and size can be used to establish identification of emission nebulae. Where a 21-cm absorption spectrum is obtained, it may offer definite evidence of identification in the case of a galactic object. In the great majority of cases, however, the prime evidence for identification is a precise position of the radio source.

Identifications of individual sources are closely allied to other investigations such as studies of the physical parameters of the sources and their spatial distribution. Any result on statistics of sources has to be considered in terms of the known identification, and a new group of identifications may demand reconsideration of statistical studies. The physical parameters such as size and spectrum of the identified sources can assist in identification of other objects for which similar parameters are known. Historically, in the study of the

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*Introductory talk at the session on discrete sources at the U.R.S.I. General Assembly, London, September, 1960.

sources, emphasis has switched from time to time between the foregoing types of investigation. As this is essentially an historical survey, it will intermix the various investigations, stopping at certain points to summarize the best data on particular types of objects.

Some twelve years ago, only six radio sources were known, half of which were identified with visible objects. These were among the brightest radio stars and simple interferometric equipment of low primary resolving power was adequate for the determination of position; Identification was relatively easy, as the optical counterparts were moderately bright and of appreciable angular extent. The two brightest radio stars, Cyg-A and Cas-A, were not identified until 1951. Here again simple interferometers were used, but more care was taken with determination of instrumental constants. The optical counterparts are visually very faint objects.

In order to detect fainter and fainter radio sources, it became necessary to build larger and larger antenna arrays to secure both increased signal-to-noise ratio, necessary for detection, and higher resolving power, necessary to discriminate against the confusing effects of the bright sources. Most of the work on discovery of the sources and the compilation of catalogs has been done by two groups, one at Cambridge and the other in Sydney. In both cases, the methods adopted to gain the high resolving power resulted in a loss of positional accuracy over the early simple interferometers. At Cambridge, interferometry was still employed but with larger primary elements. However, chiefly due to financial reasons, the gain in resolving power was made principally in one direction, east-west. While in the absence of confusion very high accuracy could be obtained in right ascension, the primary resolution in declination was relatively poor, and owing to the short time of observation, the period method for determination of declination gave results of fairly low accuracy. In Sydney the Mills Cross antenna was used for both discovery and position work. Here the positional accuracy was principally limited by signal-to-noise ratio, rather than confusion, but was equal in both coordinates and probably somewhere intermediate between the accuracy of the Cambridge right ascensions and declinations.

By 1957 several thousand radio sources had been observed by the two groups, but the number of identifications had increased by only a small factor. In fact, very few identifications had come from the meter-wavelength survey work; the majority were the result of deliberate attempts to detect radiation from known optical objects such as the nearby galaxies (principally by the Manchester group), and emission nebulae and planets (principally by the U. S. Naval Research Laboratory). Successive efforts by Minkowski, Mills and Dewhirst, using the Cambridge and Sydney catalogs, failed to secure any really positive identifications of extragalactic objects although quite a number of possibilities were suggested. Dewhirst in particular noticed a more than chance coincidence in the number of double elliptical systems near the positions of radio sources.

In the three years since the Boulder conference, the identification rate has increased. This has been partly due to the construction of large precise steerable reflectors working in the decimeter range, and two new interferometers, one at Cambridge and the other at the California Institute of Technology. Both the Cambridge and Caltech instruments have baselines whose length and axes can be changed.

At this stage, I propose to turn to discussion of identifications, starting with the nearby objects of the solar system and the galaxy, before returning to the more controversial questions of extragalactic identifications and statistics of source distribution.

Sources in the Solar System.

A short summary of results on the moon and planets is given in Table 1. Probably of greatest interest is the high intensity radiation in the decimeter band from Jupiter. Radhakrishnan and Roberts[1] have shown that this is about 30% linearly polarized with the electric vector parallel to the planet's equator. The linearly polarized part probably comes from a belt at 3 times Jupiter's radius with the randomly polarized component somewhat closer to the planet. There is a strong similarity between the belt and the earth's outer van Allen belt, though the electron density and magnetic field may be higher by several orders of magnitude. The rather high disk temperatures for Venus suggest that there might be a somewhat similar phenomenon. Observations have been attempted at 31 cm, with the result of an upper limit of less than 2000° for an equivalent black body temperature. It is probable that the 8-mm observations refer to the upper atmosphere and perhaps the 3 and 10-cm results to the surface of the planet. The suggested observation of low frequency burst-type radiation from Venus has now been retracted[2]. Two observations have been reported of radiation from Saturn, one of the presumed black body radiation at 3.75 cm, and one of a burst-type radiation at 23 Mc/s similar to that from Jupiter. For the latter, the investigators[3] do not themselves consider their evidence certain, and in the former the investigators[4] offered no proof that the planet was the source of radiation.

Galactic Sources.

Nowadays we make an automatic subdivision of the cosmic radio sources into the two distinct classes of galactic and extragalactic emitters. The probable existence of two such classes was first suggested by Oort and Westerhout[5] on the basis of early surveys by Ryle and Smith[6] and Stanley and Slee[7]. Definite proof was first established by Mills[8], both from number-magnitude counts and from the obvious concentration of bright sources towards the galactic plane. Subsequent surveys, particularly at the shorter wavelengths, have merely reinforced Mills' findings.

About 40 percent of the known galactic sources can be identified, exclusively either with emission nebulae or supernova remnants. Of 110 objects listed by Wilson and Bolton[9] which are probably galactic, there are 58 for which approximate radio spectra and diameters are known. These comprise 33 emission nebulae, visible on the 48" Schmidt plates, 9 objects which are probably emission nebulae (the regions of these sources are heavily obscured), 13 supernova remnants or likely supernova remnants, and 6 objects which have non-thermal spectra in regions which are heavily obscured.

Table 2 lists the radio sources above declination -50° that can be associated with visible emission nebulae. The values for flux density at 960 Mc/s are from Caltech observations. In comparing the integrated flux densities with those of other workers, for instance Westerhout[10], note should be taken of the assumed angular size used in obtaining the integrated flux. The values depend greatly on whether an estimate has been made from comparison of the antenna beam and source profile, the optical size or an interferometric determination of the brightness distribution. Similar care should be taken in considering the low frequency intensities, for, as Mills[11] has shown, absorption effects can become serious and in some cases emission nebulae appear as 'holes' in the background continuum.

Table 3 lists the radio sources which are probably emission nebulae, but which are not visible on the Schmidt plates due to obscuration.

Table 4 lists 13 objects which are, or may possibly be, supernova remnants. Only three of these objects are definitely supernova remnants. In these cases the initial outbursts were observed and from the distance of the present remnants it can be shown that the absolute luminosity was of the right order for a supernova explosion. In a number of other cases (Cas-A, Cygnus Loop, IC-443 and Pup-A), energy of the order involved in a supernova is required to account for the mass and motion of the presumed remnant.

The remaining six objects are judged to be supernova remnants purely on their appearance and similarity to more certain identifications, plus the fact that the radio emission appears to be non-thermal.

In 1958, Drake and Ewen[4] reported detection of radio emission from two planetary nebulae, NGC 6583 and NGC 7293, at a wavelength of 3.2 cm. Since then, T. A. Matthews has calculated the expected radiation from a number of planetary nebulae on the basis of the free-free mechanism using photoelectric data on Hα emission. For one nebula, NGC 7009, similar calculations have been made by L. H. Aller, using a slightly different method. His results are within 20 percent of that of Matthews. Matthews has also made a careful search for the radiation from about 12 objects, finding possible emission at about the expected level and position from two, any emission from the remainder being below the limit of his receiver sensitivity. The results for four are given in Table 5. For NGC 6543, the position of the source agrees well with that of the planetary. NGC 7009 is superimposed on a more extended source; the position agrees well in declination, but only fairly well in right ascension. Near the position of NGC 6853 there are rapid changes in the galactic background and NGC 7293 is near the edge of an extended source. These factors make observations difficult and are responsible for the rather high upper limits, and possibly for the apparently erroneous results of Drake and Ewen.

Old novae have also been investigated as possible galactic sources. D. E. Harris has recently made observations in the positions of about ten old novae at 960 Mc/s with negative results. The limit of sensitivity of his equipment was about $3 \times 10^{-26} W\ m^{-2} (c/s)^{-1}$.

It appears that only the emission nebulae and supernova remnants are notable discrete sources of radio emission in the Galaxy. In general these galactic sources are distinguished by the fact that the radio brightness distribution follows very closely the optical distribution. This means that where a radio diameter is known, one can search the plates for a galactic object of the same diameter. This is in strong contrast with the extragalactic sources where the ratio of radio diameter to the optical diameter ranges between 1 and 30. Knowledge of the radio diameter only indicates the magnitude of the expected identification within a range of perhaps 5 magnitudes. Galactic sources may also differ from extragalactic sources in the range of their spectral indices. Harris and Roberts[12], from a comparison of the 3C source intensities at 180 and their own measurements at 960 Mc/s, suggest that the extragalactic objects have a very small range in spectral index (perhaps $\pm$ 0.2), whereas the range for galactic objects may be as high as $\pm$ 0.6.

Most of the galactic objects in unobscured regions can be identified. At the short wavelengths, practically all of the radiation within $\pm 60^{\circ}$ of the anticenter resolves into sources of angular size between 5' and 2°, and nearly all occur in regions where absorption is sufficiently small to permit the visual counterpart to be seen. In the Cygnus region where we look almost along a spiral arm, practically all the radiation resolves into discrete sources, but high absorption permits visual identification of only the nearer sources. Towards the center an increasingly smaller part resolves out and only about one-third of the resolved objects are sufficiently nearby for visual recognition.

One question on galactic sources is whether they alone account for the galactic continuum radiation. The high frequency results within $\pm 60^{\circ}$ of the anticenter would certainly suggest this possibility. Objects as physically large as some of the old supernovae, lifetimes of the order of that of the Cygnus Loop and a frequency of occurrence of 4 per thousand years, would give dilution factors exceeding 1 in the section of the galaxy towards the center and could well give the impression of an unresolved continuum. Mills[11] has suggested that perhaps the supernova remnants provide a source of relativistic electrons which then radiate in a general interstellar magnetic field. Whether it is the supply of electrons from the remnants or a steady expansion of individual cohesive remnants into an apparently continuous background, the supernova origin is very plausible.

The Radio Galaxies.

Studies of a number of nearby galaxies have been made by Hanbury Brown and Hazard[13] in the northern hemisphere and by Mills[14] in the southern hemisphere. Although earlier results were somewhat discordant, the most recent[15] show that the apparent radio magnitude for Sb's and Sc's defined by

$$m_r = -53.4 - 2.5 (\log S)$$

where S at 160 Mc/s is in units of 10^{-26} watts $m^{-2}(c/s)^{-1}$ is equal to the apparent photographic magnitude. For a sample of 20 galaxies, the dispersion is only 0.5 magnitudes. The radio emission from irregular galaxies is somewhat lower, and from ellipticals probably very much lower. Considering these nearby systems as normal, about 0.1 percent of all galaxies are abnormal, emitting at levels of up to 10^6 times that of a normal system.

Ten years ago, following a very precise position of the Cygnus-A source due to Smith[16], Baade and Minkowski[17] identified this source with two members of a distant cluster of galaxies in collision. The distance of this pair is about 2×10^8 parsecs and the collision between the interstellar gas masses gives rise to enhanced emission lines. These strong lines permit an easy measurement of the red shift, in contrast to the weak absorption lines in normal systems. This identification raised two exciting possibilities. Firstly, the radio sources might lead to other and more distant collisions in clusters and thus pre-select objects for extending the optical red shift measurements to a greater distance than normally possible. Secondly, through a study of the distribution of radio galaxies, it appeared possible that radio astronomers could make an independent attack on the cosmological problem.

In 1955, the first large-scale survey for extragalactic sources by the Cambridge group using the large four-element interferometer produced the startling result that the number of faint radio stars increased considerably faster than would be the case for a uniform isotropic universe. Identifying the typical source with Cygnus-A, Ryle and Scheuer[18] provided a ready explanation in terms of a distribution of Cygnus-A type objects, mostly at very great distance. Looking out into space, and thus backward into time when matter in the universe was closer together, more frequent collisions between galaxies could account for the observed effects. The ensuing debate centered around two main questions, first whether the basic data was correct and second, whether alternate explanations were possible in terms of a peculiar luminosity function. The first data available from the Sydney cross gave a much smaller excess of faint sources than the Cambridge result and it was pointed out by the writer that any observational errors in the measured magnitudes which increased with increasing faintness would produce the excess effect, whether it was due to confusion between adjacent sources, as in the case of the Cambridge survey, or to a sensitivity limit as in the case of the Sydney survey. An examination of one area of sky common to both the 2C and the Sydney survey revealed very large discrepancies except for the brightest sources. This major discrepancy has now been shown to be largely due to errors in the 2C catalog, caused by over-analysis of the results. A further survey, 3C[19], was then made with the same antennas at double the frequency (i.e. primary beam only 1/4 that of 2C). This contains only 500 sources instead of the 2000 in 2C. The agreement with Sydney is much better in the common area, the main point of disagreement being on the existence of extended objects in the Sydney source list. The statistics from 3C still give an excess of faint objects, though it is the inclusion of rather bright extended objects (which they have been unable to confirm observationally) that depress the slope in the Sydney results. Observation both by the Manchester and the Caltech groups do confirm the existence of extended sources, though some objects classed as extended by Mills, Slee and Hill[20] may not be really extended, and others may be due to blends of two or more sources. It is clear that a genuine extended source is included by Cambridge if it is sufficiently far away to be unresolved and therefore omission of such objects nearby would produce a steeper slope than is actually the case for the log N-log S curve. It is interesting to note that the new data from 3C has a slope of -2.0 and from the Mills, Slee and Hill survey for the zone +10° to -20° in declination is -1.8. If the extended sources are omitted in the latter, the slope is increased to -2.0; however, the authors suggest that corrections for the effect of observational errors would reduce the observed slope of -1.8 to -1.65.

We have made some attempt at Caltech to resolve these differences by making sample checks of the individual catalogs. A check on the sources in the 3C catalog has been made at 960 Mc/s by Harris and Roberts using a 90' equatorially-mounted reflector. Their results on approximately one-hundred sources are as follows.

1. One was not found.

2. Two others were found to be a single source on an intervening position.

3. For 47 of the sources the differences between the 3C and Caltech positions were greater than the sum of the errors.

4. Omitting obvious galactic objects, the spectral indices based on the 3C value at 160 Mc/s and Caltech at 960 Mc/s show an extremely small dispersion.

Initially, observations of intensity were made on the assumption that the 3C positions were correct. Due to some measurements being made in incorrect positions, these observations led to the finding that the fainter sources had apparently steeper spectra than the brighter ones. As the identified radio sources cover a very large range in intrinsic luminosity, such a result would not be anticipated. The anomaly disappeared after observations were made at corrected positions. The result on the uniformity of spectral index is an important one, for it indicates that the frequency of observation will not seriously affect statistical studies, e.g. the number magnitude relation.

A similar investigation was carried out on one area of the Mills' cross survey, this time using two 90' reflectors as an interferometer (fringe spacing 20'). Observations were made of 450 sources, at the positions given by Mills. The results for the 306 of these sources whose flux density at 85 Mc/s is greater than 15×10^{-26} W $m^{-2}(c/s)^{-1}$ are as follows.

1. For the 216 sources not noted as extended or probably extended, evidence was found for 161 (75%).
2. For the 47 sources noted as probably extended, evidence was found for 22 (47%).
3. For 43 sources noted as extended, evidence was found for 24 (56%).

Twenty-six of the extended sources and 30 possibly extended sources in the catalog were also observed with a fringe spacing of 30' with the following results.

For 26 extended sources:

(a) 10 gave equal amplitudes at both spacings;

(b) 4 were not seen with the 20' fringe spacing, but were seen with the 30' spacing;

(c) 4 were not seen with the 30' fringe spacing, but were seen with the 20' spacing;

(d) 8 were not seen at either spacing.

For 30 probably extended sources:

(a) 16 gave equal amplitudes at both spacings;

(b) 6 were not seen with the 20' fringe spacing, but were seen with the 30' spacing;

(c) 3 were not seen with the 30' fringe spacing, but were with the 20' spacing;

(d) 5 were not seen at either spacing.

It would appear that about half the sources reported as extended or possibly extended are really effectively point sources (those in category a). A small number, those in category b, are genuine extended objects and some or all of those in category d could also be extended and fully resolved at both spacings. Objects in category c are probably blends of one or more sources.

An examination of the spectral indices gave much the same result as was the case with the initial examination of the 3C sources, i.e. the fainter sources have apparently steeper spectra. At a level of 15×10^{-26} W m^{-2}(c/s)$^{-1}$ the ratio of flux density at 960 Mc/s to that at 85 Mc/s was lower by a factor of 2 than for the strong sources. Mills, Slee and Hill (unpublished) suggest that their values are overestimated by about 20 percent at this level; probably the remaining discrepancy is due to positional errors. A sample check on 10 objects which have relatively flat spectra (i.e. are relatively intense at 960 Mc/s) showed that the position errors for the weak sources in the Sydney catalog are probably underestimated and may average as high as 15'.

In general, rather better confirmation was obtained of the sources in the 3C catalog and their relative intensity than of the sources in the Sydney catalog. The extended sources of the Sydney catalog in some cases do not appear to be extended and in others are complex, perhaps blends. I must stress that this conclusion is not very firm, but at the moment I find it difficult to believe that the slope of the log N-log S relation can be forced down to -1.5. Whether the interpretation of a greater slope proposed by Ryle and Scheuer is correct, or whether an alternate explanation exists -- for instance in terms of the luminosity function -- is another question. It seemed worthwhile, however, to examine rather closely their main premise, that the extragalactic radio sources are mainly objects of high intrinsic luminosity at great distances. In the past year, measurements by Elsmore, Ryle and Leslie[21] at Cambridge with a complex interferometer, by Harris and Roberts at Caltech using a single high-resolution telescope, and by Matthews, Read and Morris at Caltech using an interferometer have resulted in highly accurate positions for about a hundred of the brightest radio sources. Many of these measurements provide excellent cross checks of the accuracy of the individual results, establishing beyond any doubt that a radio source is definitely within a certain small area, generally of one to three square minutes of arc. The area of each source has been classified on the 48" Schmidt plates in the following way.

Field Class I. A single prominent object virtually alone within the error area. Generally brighter than 17th magnitude;

Field Class II. More than one object brighter than the plate limit requiring positional accuracy better than 0'.5 in both coordinates to make a definite identification. Between magnitudes 17 and 19.5;

Field Class III. Many faint objects towards plate limit, 20th magnitude;

Field Class IV. Field heavily obscured.

Neglecting about a quarter of the objects which are in Class IV, the division of the remainder between the various classes was I - 15%, II - 30%, III - 55%. Most of the objects in Class I had been suggested as possible identifications by Dewhirst, Minkowski or Mills and nearly all these suggestions have been confirmed by subsequent Cambridge or Caltech measurements. The rather high number in Class I relative to II and III indicates a high proportion of radio galaxies in the low end of their luminosity function. It is perhaps of interest to question whether the luminosity function can be extended down to the so-called normal galaxies. One apparent objection to this is that all the normal galaxies detected are either spirals or irregulars, whereas the radio galaxies are, with a few notable exceptions such as NGC 1275, E's or SO's.

The objects in Class III (55% of the total) must be fainter than magnitude 19.5. Now, as most of the identified objects are galaxies of high intrinsic luminosity -- and we can only extrapolate reasonably on the basis of known identifications -- these must be more distant than $\sim 10^9$ parsecs. Except perhaps in a most exceptional case, i.e. where the strength of the emission lines is on a scale equal to or greater than that of Cygnus-A, these objects are out of range for spectrographic investigation and many of them may well be outside the range of direct photography. The positions investigated represent those of about half of the 200 brightest radio stars. It is clear from these considerations that many of the sources do suit the hypothesis made by Ryle and Scheuer.

A second approach may be made through the radio luminosity function for the abnormal galaxies. Table 6 contains a list of what I consider certain identifications and, below the space, very probable identifications. In this table are given the optical positions, the angular sizes, mainly due to Moffet and Morris, red shifts, due to Minkowski, radio magnitudes deduced from the red-shift and the flux densities at 960 Mc/s. The flux densities at 960 Mc/s have been multiplied by 3.5 to correct to the standard frequency of 160 Mc/s, as direct measurements at this frequency are not available for all the sources listed. An average photographic magnitude of -20.5 for all the objects for which red shifts are known was computed and used to determine the distance modulus and thus M_r for the others. All the sources except three which are shown with horizontal bars through them in Figure 1 are in an area of 5 steradians. Those for which identification is still uncertain are shown as open circles.

The data of Figure 1 was used to compute the luminosity function in Figure 2 (open circles), which shows the number of radio galaxies per cubic megaparsec in a given range of magnitude. Very similar results over a smaller range in M_r have been obtained in unpublished work by both Minkowski and Mills for possible identifications in the zone 10° to -20° of the Sydney catalog. The slope for a large section of this curve where the data must be essentially complete is about 0.5. This is the divergent condition (< 0.6) where each magnitude range contributes more objects than the range below for sources in a given range of apparent magnitude. In order to bring the total counts up to the observed values it can be shown that the density at $M_r = -35$ has to be increased by an order of magnitude. At present we cannot say where the luminosity function may reach the convergent condition beyond $M_r = -35$. The red shift correction whose form is not known yet at the distances implied by $M_r = -35$ would probably be a major factor in producing an effective convergence. However, it is clear that source statistics even in the first hundred or so are undoubtedly affected by large-distance phenomena.

The luminosity function may also be derived from the distribution of angular diameters of the radio galaxies. The most detailed data on diameters is that from the work of the Manchester group and from the work of Moffet at Caltech. The former measurements were made on 301 objects, at two antenna spacings of 2200 λ and 9700 λ; and the latter on 108 objects at twelve spacings between 130 λ and 1600 λ; all the objects are from the 3C catalog. I am indebted to Professor A. C. B. Lovell for communicating the Manchester results in advance of publication. The Caltech observations give more detailed results on the objects of diameter greater than one minute of arc, and the Manchester observations select objects with features of angular size less than a minute of arc. Both sets of observations indicate that many of the sources are complex. Sixteen percent of the sources observed at Manchester give fringe amplitudes at 9700 λ <u>greater</u> than at 2200 λ. Nine out of 16 sources observed by Moffet, for which the fringe amplitude goes to zero before 800 λ, give indications of a second maximum approaching the first in amplitude.

In Figure 3 are plotted the angular diameters and distances of the identified radio galaxies. Due to the complexity in many sources, the angular diameter has been defined as the half width of the equivalent-disk Gaussian-distribution gained from that part of the amplitude-spacing spectrum between the initial maximum and the first zero. There is obviously a large dispersion in the physical dimensions of the radio galaxies, some of which must be due to orientation, but the median size is around 80 kiloparsecs. A radio galaxy of apparent diameter of 1' is thus at a mean distance of 3.5×10^8 parsecs.

The combined angular size data from Manchester and Caltech is given in Table 7. Due to the larger number of baselines used in the Caltech observations, a finer subdivision can be made of the Caltech data. There is good agreement in the fraction of sources down to $3\overset{'}{.}2$ angular diameter, but poorer agreement in the distribution below this diameter. However, the 2200 λ - 9700 λ anomalies for the sixteen percent of the sources were ignored in tabulating the Manchester data. Using the previously stated definition of diameter, some of these objects should no doubt be transferred from the final category to the earlier ones which would tend to resolve the discrepancy.

On the basis of an average size of 80 kiloparsecs, the Caltech distribution has been converted to a luminosity function and the individual points are shown as filled dots in Figure 2. The relation between

M_r and m-M was used to determine the location of the abscissae. There is very close agreement with the faint end of the luminosity function derived from the identifications and with the revision of the bright end required by the number counts. The final point includes all sources of diameter less than 0ʹ.4 and thus represents an upper limit.

Some Remarks on Classification of Identified Radio Galaxies.

In view of the increased number of identifications now available, it seemed worthwhile summarizing their parameters and their interrelationships of these parameters in the hope of pointing to the mechanism or evolution of these systems. The available parameters are, on the optical side, the luminosity, spectrum, type and cluster membership, and on the radio side, luminosity, spectrum and angular size.

The radio galaxies appear to be mainly systems of high absolute brightness. For those systems whose red shifts are known or assumed, the average absolute photographic magnitude is -20.5. This includes NGC 4782/3, which has been assumed to be a member of the Virgo Cluster and for which on this basis M = -17.6. Both M_r and the angular size are abnormally small; thus it seems possible that this system may not be a cluster member. Omitting it, the mean photographic magnitude becomes -20.8.

Optical spectra in general are not particularly abnormal; some do show moderately strong emission lines, but then so do some other galaxies which are not radio emitters. Notable exceptions are Cygnus-A and 3C-295, for which M_r is brighter than -33. In Cygnus-A half the light of the galaxies is in emission lines; in 3C-295 20 percent of the total light is in the O[II] lines which are shifted to the red by 0.46. This system is a member of the most distant cluster known, and its recent identification by Minkowski was due to the knowledge of the angular size ($<$ 0ʹ.2) from Manchester measurements, and precise positions from Cambridge and Caltech. M87 has a minor spectral anomaly in its blue polarized jet; one other system, 3C-66, may have a similar but somewhat more conspicuous jet. Minkowski has attempted to detect polarization of the jet in this object, which is 3 magnitudes fainter than M87, but without success.

Many of the radio galaxies are in clusters or small groups of galaxies. With the limited numbers available it is difficult to say whether the proportion is significantly greater than for all galaxies. There are, however, undoubtedly some radio galaxies which are field galaxies, so that radio emission is not entirely exclusive to cluster membership. The number of pairs, however, is significant: 11 radio galaxies are doubles, as against 14 singles. While radio emission does not demand a double system, it would appear probable that the close presence of one galaxy is likely to trigger the mechanism in the other.

The identifications, where type can be established, are mostly E's and SO's. For distant systems, classification is very difficult. Baade and Minkowski classified Cygnus-A as a pair of Sb's; however, this classification is somewhat uncertain. It was presumably based on the presence of the strong emission lines, which suggests considerable gas content for the galaxy, rather than on appearance. Of the nearby systems, NGC 1068 and 1275 are the only certain spirals -- the latter being a pair. As the stellar populations and structure of the nuclei of spirals bear considerable similarity, and if the nuclear region is responsible for the initiation of the radio mechanism, emission from a spiral might be anticipated in occasional circumstances whereas in general spiral structures will inhibit the radio mechanism. In passing, it may be noted that the Sag-A source at the center of our own Galaxy has a volume emissivity comparable to that of the brightest radio galaxies.

On the data available at present, it appears that the radio spectra of most radio galaxies are remarkably similar, with an index of approximately 0.7. Two exceptions are NGC 1068 and the jet in M87. In NGC 1068, the source is considerably smaller than the galaxy and its spectral index is probably about 0.4. The brightness distribution of M87 is double. There is an extended source of the order of 10' and a source smaller than 1'. Comparing the amplitude-spacing spectra given by Mills at 101 Mc/s and unpublished results of Moffet at 960 Mc/s and Denisse at 1420 Mc/s, the spectral index for the large sources is approximately 0.8 and that of the small source 0.3. The small source is presumably to be associated with the jet. It is interesting to note that the two radio stars which exhibit optical synchrotron radiation, M87 and the Crab Nebula, have similar radio spectra. There appears to be little correlation between the absolute radio luminosity of a galaxy and size of the radio source, except for a suggestion from only three objects that a small source is intrinsically weak. These three are, however, 3C-317, NGC 4782/3 and NGC 1068. The latter, as has been previously indicated, may be something of a special case; there is a doubt on the distance to NGC 4782/3 which, if increased, would make the object conform better; and 3C-317 is only a possible identification. The median value of the physical diameter, defined in the manner previously stated, is around 80 kiloparsecs. Some are as large as 300 kpcs and the total extent, as in the case of NGC 5128, may approach 1 Megaparsec.

A considerable number, exceeding 30 percent of the sources, are double objects of almost equal intensity. The doubling is not necessarily correlated with optical doubling. There are some cases of double radio and double optical, some optical double, but apparently single radio sources, and vice versa. Some objects such as NGC 5128, M87 and NGC 1275 have more complex distributions still. In 5128 there may be two pairs of extended sources, plus a third pair of small sources. In general, the individual components of a double seem well separated.

It is of interest to consider the possible time scale of the radio galaxies whose sizes range up to fifty times that of the presumed optical counterparts. The two sources of Cygnus-A are some 3×10^4 parsecs from the parent galaxies. These, from the emission lines, are probably still in collision at a relative velocity of 3000 km/sec. Unless the radio emission started long before physical contact, it is necessary to assume the radio sources emerged at a velocity considerably in excess of the collision velocity and thus of normal shock velocities. For higher velocities it would be necessary to involve particle velocities of the order of the velocity of light. In this case, the lifetimes would be quite short, of the order of 10^6 years, even for sources as large as NGC 5128. This would explain why we see so few radio galaxies; it is in fact too few, if we consider the radio galaxies are only systems of high intrinsic luminosity. One possibility is that the radio phenomenon is recurrent and support for this might be indicated by the multiple pairs in NGC 5128 and the point source plus halo distributions of some other sources.

Acknowledgements.

I am indebted to the staff and student members of the California Institute of Technology Radio Observatory for much of the unpublished data used in this paper. The work of this observatory is supported by the United States Office of Naval Research under Contract Nonr 220(19). I wish to thank Dr. Rudolph Minkowski for contributing optical data and for discussion on many points.

Legends for Figures.

Figure 1. Absolute radio magnitude and distance modulus (or distance) for the identified radio galaxies. Uncertain identifications are shown as open circles, and certain identifications not in the area used to determine the luminosity function are shown with a horizontal bar. The cut-off to the lower right is the sensitivity limit.

Figure 2. The luminosity function for radio galaxies. Open circles are from the identifications of Figure 1 and Table 6. The increased slope beyond $M_r = -30$ is presumably due to incompleteness. The full line is required by source counts. The filled dots are the luminosity function deduced from the distribution of angular size; the final point at $M_r = -31.5$ is an upper limit as it includes all sources $< 0\overset{'}{.}4$.

Figure 3. A plot of angular size against distance modulus (or distance) for the identified radio galaxies. Open circles are uncertain identifications.

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ADDENDUM - July 6, 1960.

Prompted by the apparent anomaly of the source NGC 4782/3, Dr. Jesse L. Greenstein obtained spectra of the two objects in this system at the prime focus of the 200" telescope. He obtained red shifts of +3870 km/sec for NGC 4782 and +4540 km/sec for NGC 4783. The galaxies are thus not low-luminosity objects in the Virgo cluster, but high-luminosity objects at greater distances. The absolute luminosity corresponding to the mean red shift is -20.4 and the absolute radio magnitude -25.8. Appropriate corrections should be made to Table 6 and to Figures 1 and 3.

Table 1

Radio Sources in the Solar System

Object	Disk Temperature Black Body	Non-Thermal Radiation
Moon	183° at 3.2 cm	not observed
	270° at 21 cm	
	250° at 31 cm	
Venus	580° at 9.4 cm	not observed
	560° at 3.15 cm	
	410° at 8 mm	
Mars	218°	not observed
Jupiter	$\sim 140^{\circ}$ at 3.15 cm	$\sim 8 \times 10^{-26}$ W $m^{-2}(c/s)^{-1}$ between 400 and 3000 Mc/s. Short period high energy bursts ($\sim 10^{-20}$ W $m^{-2}(c/s)^{-1}$ in the 10-20 Mc/s region.

Table 2

Emission Nebulae Which are Radio Sources

Radio Designation	Optical Designation	Position (1950) α	Position (1950) δ	Flux Density at 960 Mc/s 10^{-26}W $m^{-2}(c/s)^{-1}$	Approximate Size
CTB 2 W1	NGC 7822	$00^h00^m.5$	67°	220	2°
CTB 7	NGC 281	00 50.1	56.3	48	2°
CTB 9 W3	IC 1795	02 22.7	61.8	260	0°.3
CTB 9 W4	IC 1805	02 29.5	61.2	140	1°.2
CTB 11 W5	IC 1848	02 48	60.2	175	1°.2
CTB 12	IC 1491	04 00.8	51.2	33	0°.25
CTB 16	IC 405	05 12.4	33.6	40	0°.6
CTB 17 W8	IC 410	05 19	33.4	60	0°.7
CTA 37 W10	Orion Neb.	05 32.8	-5.4	360	P
CTB 19	Sh 232	05 37.1	26.0	20	0°.6
CTB 21 W16	Rosette Neb.	06 29.4	4.9	342	1°.2
CTB 22	NGC 2327 IC 2177	07 03	-10.7	125	1°.5
CTB 23	NGC 2467	07 48	-26.0	13^x	$--^x$
CTB 24	NGC 2568*	08 15	-36.0	8^x	$--^x$
CTB 27	Stromlo 14	08 37.6	-40.6	33	1°
CTB 30	Stromlo 17	08 48.1	-42.2	33	1°
CTB 31	Stromlo 23	08 57.4	-47.3	250	0°.4
CTB 32	Stromlo 20	08 57.8	-43.6	59	0°.7
CTB 35	†	16 57.6	-40.2	66	0°.2
CTB 39	Sh 8	17 17.7	-36	180	0°.2
CTB 40 W22	NGC 6357	17 22.5	-34.3	540	0°.6
CTB 45 W28	NGC 6514	17 58.0	-23.4	240	0°.5

Table 2 (continued)

Radio Designation	Optical Designation	Position (1950) α	Position (1950) δ	Flux Density at 960 Mc/s 10^{-26}W $m^{-2}(c/s)^{-1}$	Approximate Size
CTB 46 W29	NGC 6523	$18^h00^m.8$	-24°.4	106	0°.2
CTB 50 W35	NGC 6604	18 15.2	-11.9	350	1°
CTB 51 W37	NGC 6611	18 16.2	-13.8	106	0°.2
CTB 52 W38	NGC 6618	18 17.6	-16.2	500	8'
CTB 76	NGC 6823	19 40	23.1	370	0°.3
CTB 78	†	19 44.8	28.0	15	0°.4
CTB 91 W66	γ Cygni Neb.	20 21	40.0	800	1°.2
CTB 100 W80	NGC 7000	20 53	44.0	350	2°
CTB 103	Sh 119	21 20	44.0	80	2°
CTB 104	Sh 124	21 30.4	50.6	66	1°.5
CTB 105	IC 1396	21 35.4	57.5	210	2°.2
CTB 106	Sh 132	22 18.5	56.0	190	4° x 1°

* Note NGC has 1° error in declination.

† Not cataloged.

x Size information incomplete, flux density refers to peak only.

Table 3

Radio Sources Which are Probably Emission Nebulae

Radio Designations	Position (1950) α	δ	Flux Density at 960 Mc/s 10^{-26}W $m^{-2}(c/s)^{-1}$	Approximate Size
CTB 8, 3C 58	$02^h01^m.7$	56°.3	33	5'
CTB 33	16 31.3	-47.6	300	0°.6
CTB 53, W39	18 23.5	-12.5	200	0°.5 x 2°
CTB 55, W40	18 28.6	-02.2	26	10'
CTB 56, W41	18 31.2	-08.6	90	0°.3 x 0°.7
CTB 57, W42	18 33.8	-07.2	65	0°.3 x 0°.6
CTB 61, W45	18 54.6	08.2	22	0°.3
CTB 67, 3C 397	19 04.6	07.2	27	9'
CTB 68, W49, 3C 398	19 08.4	05.1	110	0°.25
CTB 73, W51, 3C 400	19 20.7	14.1	370	0°.3
CTB 93, W70	20 30.4	43.6	90	0°.5

Table 4

List of Radio Sources
Which are Supernova Remnants
or Probable Supernova Remnants

Object	Description	Diameter	Distance	Expansion
Crab Nebula	Remnant of Type I: polarized continuous radiation plus outer filamentary structure	5'	1000	~1000 km/sec
SN 1572	Very faint, two filaments and one nebulous arc only visible remnants	~5'	1000	(1000 km/sec assumed in determining distance)
SN 1604	Fan-shaped area of filaments plus faint wisps	~2'	350	
Cas-A	Network of fast-moving filaments and condensations. Partly obscured and in region of high interstellar density	4'	3500	7000 km/sec
Pup-A	Similar to Cas-A but much lower internal motions, probably much older	40'	~500?	50 to 100 km/sec
Shajn 147	Almost circular object formed of many overlapping filamentary arcs	3°		
Vela X	Similar to S 147	3°-4°		
Cygnus Loop	Prominent incomplete expanding shell, age > 50,000 but <150,000 years	$2\overset{\circ}{.}5$	770	60 to 115 km/sec
IC 443	Thick expanding shell or possibly 2 shells	$1\overset{\circ}{.}5$	700-2000	
HB 9	Faint patches of nebulosity with approximately circular outline	~$1\overset{\circ}{.}5$	2000?	
HB 21	Faint patches of nebulosity with approximately circular outline	~$1\overset{\circ}{.}3$	~2000?	
CTA 1	Two patches of nebulosity corresponding to the radio brightness distribution forming a rough arc	~1°		
CTB 13	Extensive region of nebulosity with suggestion of structure	~5° x 2°	~1000?	

Table 5

Observations of Planetary Nebulae

Planetary	Predicted flux density 10^{-26}W $m^{-2}(c/s)^{-1}$	Measured density at 960 Mc/s 10^{-26}W $m^{-2}(c/s)^{-1}$ (Matthews)	Measured density at 8000 Mc/s 10^{-26}W $m^{-2}(c/s)^{-1}$ (Drake and Ewen)
NGC 6543	1.5	1.3	---
NGC 6853	1.0	≤ 3	11
NGC 7009	0.83	1.3	---
NGC 7293	0.57	≤ 2	27

Table 6

Identifications of Radio Sources with "Abnormal Galaxies"

Source	Position (1950) α	δ	Size	Type	m_{pg}	S at 960 Mc/s (10^{-26} units)	m_r at 160 Mc/s	$m_r - m_p$	$V = \frac{c\Delta\lambda}{\lambda}$	M	m-M	M_r
3C 26	$00^h51^m39^s.5$	$-03°43'.0$	<1'	S0 + Sb	17 + 17	4.8	8.5	-9.5			37.5	-29
3C 33	01 06 15.6	13 04.3	1!3	E0	18.5	17.3	7.1	-11.4			39.0	-31.9
NGC 545/7	01 23 26.5	-01 36.1	6'(d)	S0 + E0	13 + 13	6.6	8.2	-4.8	(3,000)	-20.0	33.0	-24.8
3C 66	02 19 01.7	42 45.8	4'	E	13	5.9	8.3	-5.3	(6,300)	-21.6	34.6	-26.3
NGC 1068	02 40 07.0	-00 13.5	<1'	S0	10	6.6	8.2	-1.8	1,030	-20.4	30.4	-22.2
3C 75	02 55 03.0	05 49.5	3'(d)	E0 + S0	13 + 13	6.9	8.1	-4.9	2,300	-19.4	32.4	-24.3
NGC 1218	03 05 50.3	03 55.2	4' + <0!8	E	13	4.5	8.6	-4.4			33.5	-24.9
NGC 1275	03 16 30	41 19.0	5' + <0!8	Sc + Sc	13.3	19.4	7.0	-6.3	5,430	-21.0	34.3	-27.3
NGC 1316	03 20 48	-37 24	20'	S0	9.6	150	4.8	-5.2	1,730	-22.0	31.6	-26.8
Hyd-A	09 15 41.2	-11 53.1	0!8	E + E	16	67	5.7	-10.3	15,900	-20.6	36.6	-30.9
NGC 4261	12 16 50.6	06 06.2	7'(d)	E	11	50	6.0	-5.0	1,136	-19.6	30.6	-24.6
M87	12 28 18	12 40.1	10' + <1'	E	10	300	4.0	-6.0	1,136	-20.6	30.6	-26.6
NGC 4782/3	12 51 59.5	-12 17.6	2!2	S0 + E0	13 + 13	10.7	7.6	-5.4	1,136	-17.6	30.6	-23.0
NGC 5128	13 22 28	-42 45.6	4° x 1°(d) + 5' x 2'(d)	E0 + Sc?	6 + 9?	1800	2.0	-4.0	260	-22	28	-26.0
3C 295	14 09 33.4	52 26.5	<0!5	?	>20	33.6	6.4	-13.6	140,000	<-21.4	41.4	-35.0
3C 298	14 16 38.8	06 42.1	<0!5	E0	18	8.4	7.9	-10.1			38.5	-30.6
3C 310	15 02 47.7	26 12.4	1!8	E1 + E0	18.5 + 18.5	11.2	7.6	-10.9			39.0	-31.4
3C 315	15 11 30.9	26 18.5	1'	E + E	19 + 19	5.9	8.3	-10.7			39.5	-31.2
3C 327	15 59 55.5	02 06.3	2!2(d)	S0	17	10.9	7.6	-9.4			37.5	-29.9
NGC 6166	16 26 56.0	39 39.5	1!5	E	14	7.4	8.0	-6.0	8,800	-21.3	35.3	-27.3
Cyg-A	19 57 44.5	40 35.8	1!2	Sb? + Sb?	15.5 + 15.5	2150	1.9	-13.6	17,100	-21.3	36.8	-34.9
3C 433	21 21 30.9	24 51.4	0!5	E + E	17	6.3	8.3	-8.7			37.5	-29.2
3C 47	01 33 41	20 47.5	<4'	E	18.5	4.6	8.6	-9.9			39.0	-30.4
3C 98	03 56 10.5	10 17.5	2'	E2	16	13.8	7.3	-8.7			36.5	-29.2
3C 171	06 51 15	54 12.8	<1'		>20	5.1	8.5	-11.5			40.5	-32.0
3C 196	08 10 01	48 22.5	<0!2	E?	19.5?	19.1	7.0	-12.5			40.0	-33.0
3C 234	09 58 58	29 00.5	no data		19?	6.9	8.1	-11.9			39.5	-31.4
3C 280	12 54 42	47 35.3	<0!5		18.5	6.6	8.2	-10.3			39.0	-30.8
3C 317	15 14 17	07 12.3	0!7	S0	12.5	9.4	7.8	-4.7			33.0	-25.2

Table 7

Distribution of Angular Sizes of Radio Galaxies

Angular Size θ	Number of Galaxies			
	Caltech (108 objects)		Manchester (301 objects)	
$\theta > 12'.8$	4%	Total 28%	Total 27%	
$12'.8 > \theta > 6'.4$	5%			
$6'.4 > \theta > 3'.2$	6%			
$3'.2 > \theta > 1'.6$	13%			
$1'.6 > \theta > 0'.8$	12%	Total 32%	Total 24%	
$0'.8 > \theta > 0'.4$	20%			
$0'.4 > \theta > 0'.25$		Total 40%	Total 49%	19%
$0'.25 > \theta$				30%

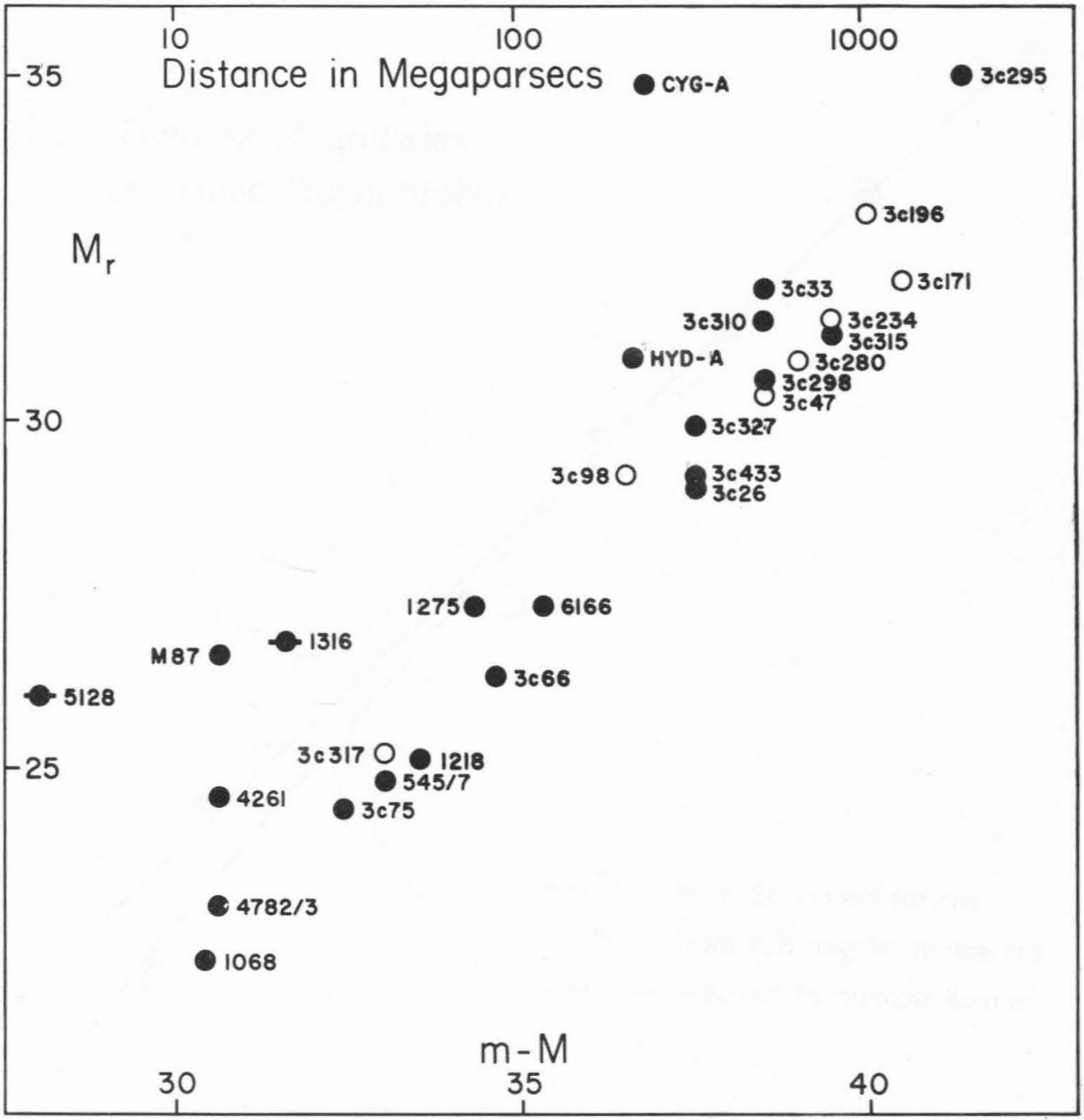
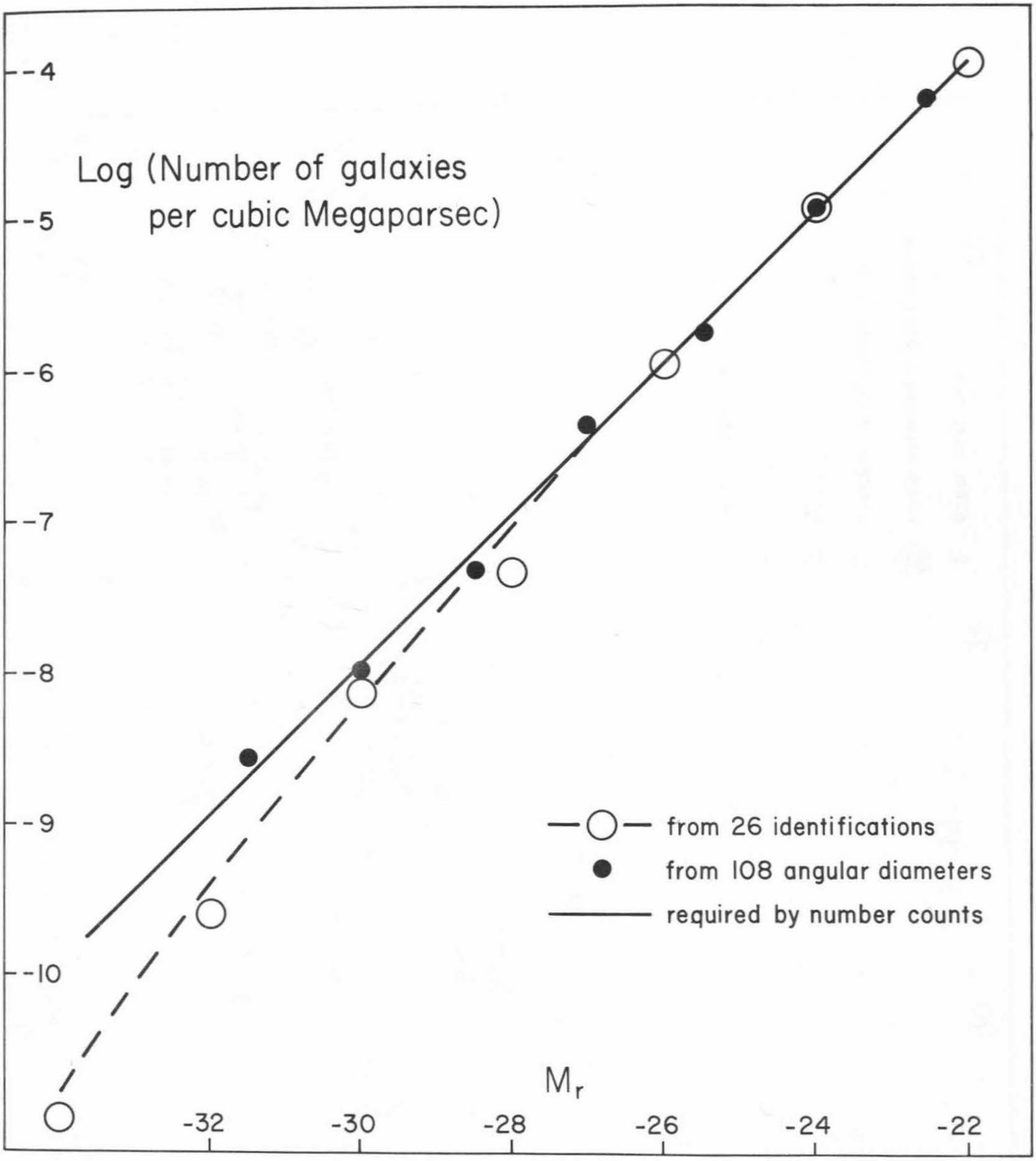

Distance in Megaparsecs
10
100
1000
M_r
35
30
25
m-M
30
35
40
CYG-A
3c295
3c196
3c171
3c33
3c310
3c234
3c315
HYD-A
3c280
3c298
3c47
3c327
3c98
3c433
3c26
1275
6166
1316
M87
3c66
5128
3c317
1218
545/7
4261
3c75
4782/3
1068

FIGURE I



Log (Number of galaxies
per cubic Megaparsec)
-4
-5
-6
-7
-8
-9
-10
M_r
-32
-30
-28
-26
-24
-22
from 26 identifications
from 108 angular diameters
required by number counts

FIGURE 2

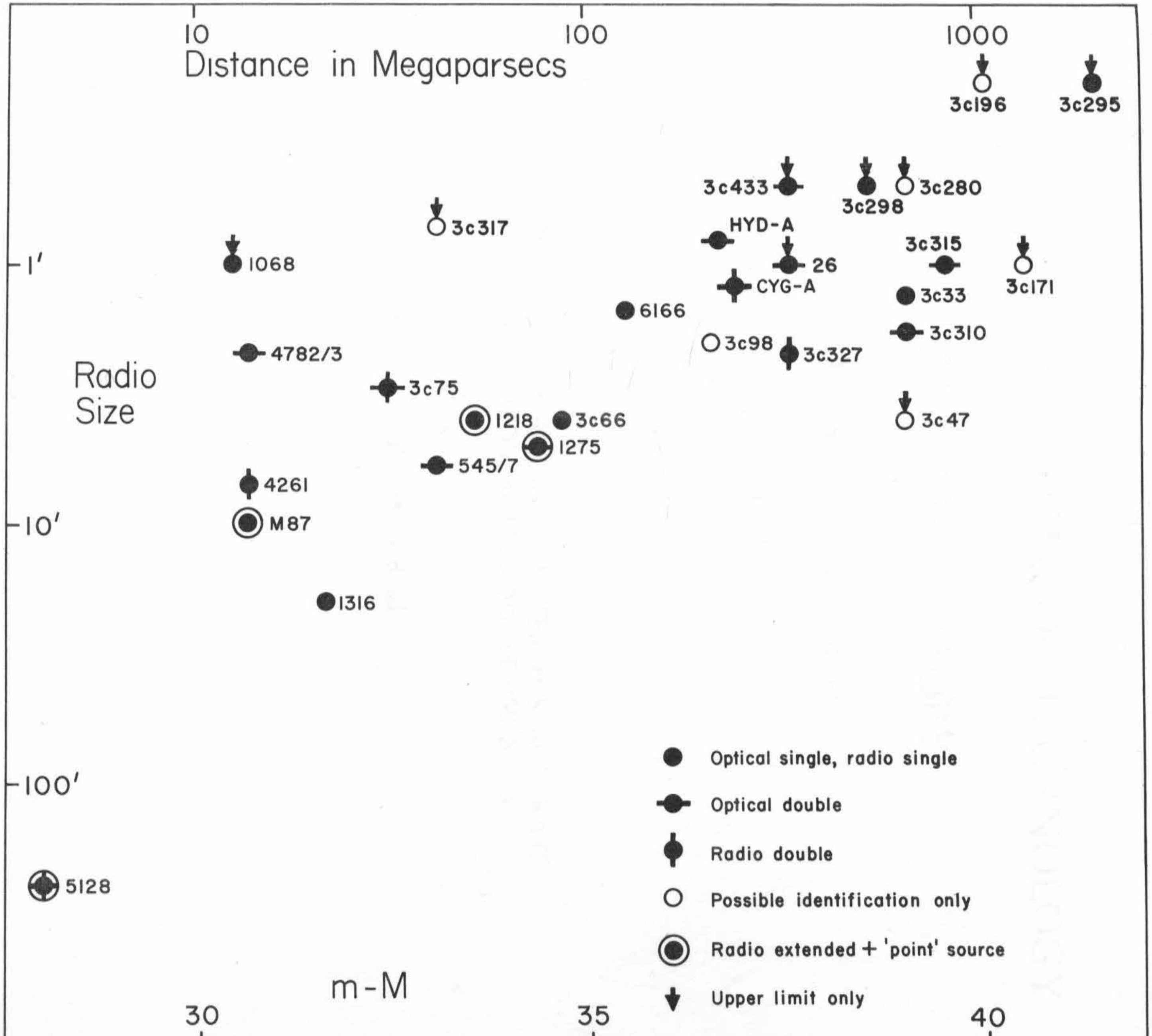

10
100
1000
Distance in Megaparsecs
3c196
3c295
3c433
3c298
3c280
3c317
HYD-A
1068
26
3c315
3c171
1'
CYG-A
3c33
6166
3c310
3c98
3c327
4782/3
Radio
Size
3c75
1218
3c66
3c47
1275
545/7
4261
10'
M87
1316
Optical single, radio single
100'
Optical double
Radio double
5128
Possible identification only
Radio extended + 'point' source
m-M
Upper limit only
30
35
40

FIGURE 3